STAFF SUMMARY SHEET

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SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Boris V. Zhdanov, Matthew D. Rotondaro, Michael K. Shaffer, and Randall J. Knize

Title: Study of potassium DPAL operation in pulsed and CW mode

Document type: manuscript for the conference proceedings

Description: In this paper the authors present results of experiments on development of the hydrocarbon free alkali laser.

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Tabs
1. Manuscript
2. Letter from funding organization (HEL JTO)

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Study of potassium DPAL operation in pulsed and CW mode

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ABSTRACT

This paper presents the results of our experiments on development of the efficient hydrocarbon free Diode Pumped Alkali Laser based on potassium vapor buffered by He gas at 600 Torr. We studied the performance of this laser operating in pulsed mode with pulses up to 5 ms long at different pulse energies and cell temperatures. A slope efficiency of more than 50% was demonstrated with total optical efficiency about 30% for the pump pulses with duration about 30 µs. For the longer pump pulses the DPAL efficiency degraded in time with a characteristic time in the range from 0.5 ms to 4.5 ms depending on the pump pulse energy and cell temperature. The recorded spectrum of the side fluorescence indicates that multi-photon excitation, energy pooling collisions and ionization may be strong candidates for explaining the observed performance degradation.

Keywords: Atomic gas lasers; Lasers, diode-pumped, DPALs

1. INTRODUCTION

There has been extensive research into Diode Pumped Alkali Lasers (DPALs) during the past decade because of their potential for efficient scaling to high powers while maintaining a high quality output beam. These lasers are often called "Hybrid Lasers", because they combine most of the important features of Diode Pumped Solid State Lasers (using an efficient diode laser pumping) and high power Gas Lasers (excellent optical quality of the gain medium). Since the first demonstration of an efficient optically pumped alkali laser in 2003 [1], and after the first Diode Pumped Alkali Laser (DPAL) demonstration in 2005 [2], significant progress in DPAL development and power scaling was achieved. There are 4 alkali atomic vapors: Cesium (Cs), Rubidium (Rb), Potassium (K) and Sodium (Na) which have each been demonstrated lasing action using optical pumping [2 - 5], and the first three of them demonstrated efficient lasing with diode laser pumping. The best results for diode laser pumping were achieved with Cs and Rb DPALs [6 - 8] including the demonstration of 1 kW output power with optical efficiency about 50% in continuous wave (CW) regime for Cs DPAL [9]. Also, power scaling experiments with multiple diode laser pump sources were performed [10 - 12], including experiments with transverse pumping [11] and an unstable cavity [12]. On the other hand, the potassium (K) DPAL, has not been extensively studied yet, in spite of its several advantages compared to Cs and Rb lasers. In particular, the K laser has higher quantum efficiency (99.6%) and can operate with low pressure noble buffer gases (He, Kr or Xe) [13], while Cs and Rb lasers can operate only with hydrocarbon buffer gases or with high pressure (several atmospheres) helium buffer gas. Both of these approaches have their disadvantages compared to the K laser. Hydrocarbon buffer gases can chemically react with alkali vapor and contaminate the gain medium with the reaction products (e.g. soot). High pressure Rb-He laser requires elevated temperatures and higher pump intensities that creates additional technical and fundamental problems especially when scaling to higher power levels.Regarding the optically pumped K laser, the best results were obtained only with so called "surrogate" (not diode laser) pump source, a pulsed (275 ns pulses) Alexandrite laser: Optical-to-optical efficiency of 57% for K laser has been demonstrated [14]. Only recently, a first demonstration of a CW diode pumped potassium laser buffered by atmospheric pressure helium was performed [15], but the slope efficiency achieved was not very high (about 25%).

In this paper we present results of our experiments with a K DPAL buffered by atmospheric pressure helium, which demonstrate 52% slope efficiency and 30% optical efficiency for the pump by pulses with duration about 30 µs and our study of the time resolved of this DPAL efficiency degradation when it is pumped by pulses with duration up to 5 msec.

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The K laser operates in a three level scheme (see Figure 1). The optical pump source excites the D2 line of potassium atom (766 nm) and lasing occurs on the D1 line (770 nm), which is only 57.7 cm^{-1} from the D2 line. To create a population inversion on the $4P_{1/2} \rightarrow 4S_{1/2}$ transition, a fast (compared to the $4P_{3/2}$ lifetime) population transfer from $4P_{3/2}$ to $4P_{1/2}$ energy states is provided by collisional mixing of these states by a buffer gas. The laser has a quantum efficiency of 99.6%, but the small separation of the pumped ($4P_{3/2}$) and lasing ($4P_{1/2}$) energy levels decreases a population inversion on the lasing transition and, hence, leads to lower gain compared to Cs and Rb vapor lasers. Lasers with a lower gain medium require a higher quality laser cavity, higher pump intensity and are very sensitive to intracavity losses. All parameters required for the small signal gain calculation for the K DPAL are provided in [15] and the calculated value is about 0.18 cm^{-1}, which is much smaller than the ones for Cs (4.5 cm^{-1}) and Rb (1.1 cm^{-1}). This means that the lasing threshold for the K DPAL has to be higher than the one for Cs and Rb DPALs.

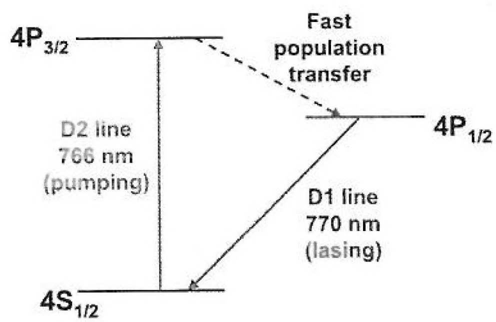

Figure 1. Potassium laser energy level diagram

2. EFFICIENT POTASSIUM DPAL OPERATING IN PULSED MODE

A diagram of the K DPAL is presented in Figure 2. We used an L-shape laser cavity with longitudinal pumping of the gain medium, similar to described in our previous experiments [13]. The 1 cm long K vapor cell had AR coated on both sides windows to minimize losses in the cell for both the operation wavelength (770 nm) and the pump (766nm). The cell was filled with metallic potassium and 600 torr of helium at room temperature before being sealed.

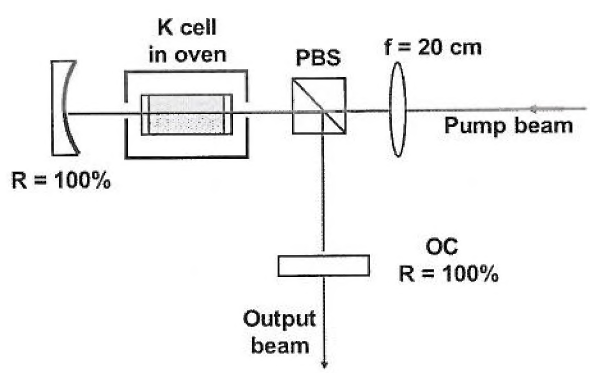

Figure 2. Diagram of the experimental setup.

The sealed cell was assembled inside an oven that could control the cell temperature while keeping its windows at about 5°C higher temperature than the cell body. The cell optimal operating temperature of 180°C was determined

experimentally by measuring laser efficiency at different temperatures. The low signal absorption of the pump radiation in the K vapor cell at this temperature is close to 100% (see Figure 3).

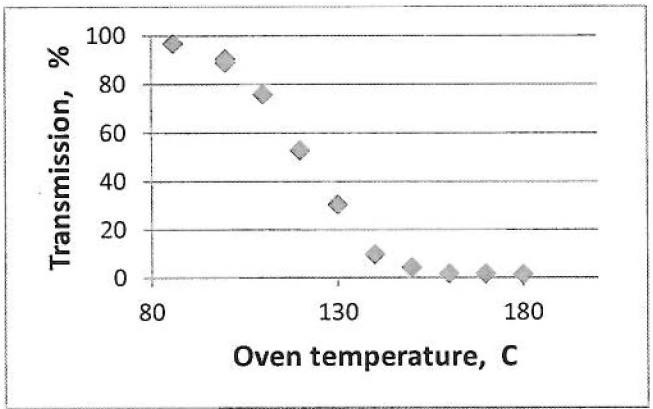

Figure 3. Experimental temperature dependence of the K vapor cell transmission for the low power pump radiation (several W/cm^2)

The K vapor gain medium was pumped by a diode laser stack operating at 766 nm. The stack emission line was narrowbanded to the value less than 20 GHz (FWHM) centered at 766nm using technique similar to described in [16]. The stack operated in pulsed mode with pulse duration about 30 μs and rep rate 100 Hz. Maximum peak power of the pump delivered into the gain cell in these experiments was approximately 50W.

The stack's output beam had a rectangular cross sections with a vertical to horizontal sides ratio of about 4 : 1. To correct the beam and make it close to square before focusing into the gain medium, we used a system of cylindrical and spherical lenses with total focal length of about 20 cm. The beam was focused into the center of the K vapor cell and aligned collinearly with the laser cavity axis to provide longitudinal pumping. Such a combination of cylindrical and spherical focusing lenses provided a satisfactory pump beam size matching to the laser cavity mode size in the gain medium. The polarization of the pump beam was orthogonal to the laser beam polarization making it possible to separate the pump and lasing beams using polarization beam splitter (PBS). The stable 40 cm long laser resonator was constructed of a 50 cm radius concave mirror with 99.9% reflection at 770 nm and 766 nm and flat output coupler with an experimentally optimized 60% reflection at 770 nm (see Figure 4).

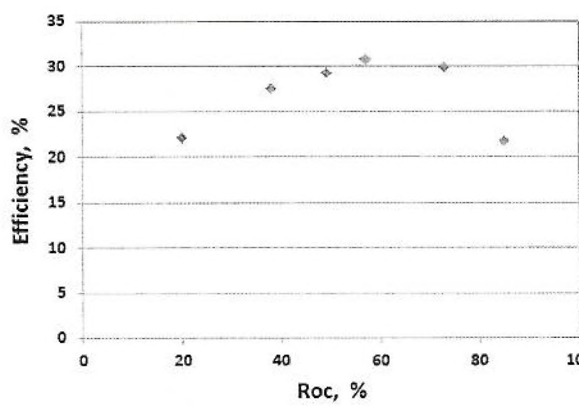

Figure 4. Optimization of the output coupler

The dependence of the K DPAL output peak power with respect to the pump peak power is presented in Figure 5. The lasing threshold appeared to be about 22 W or approximately 4 kW/cm^2. The slope efficiency was 52% and the total

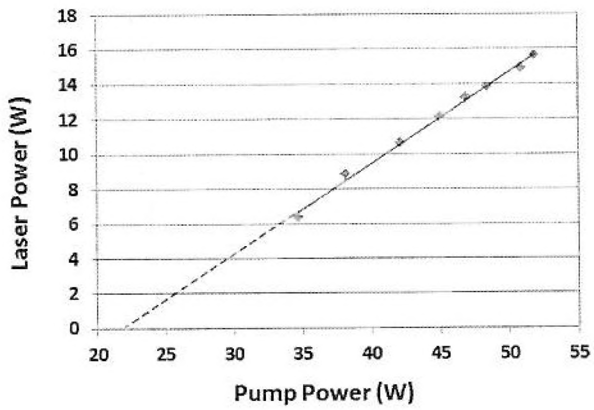

Figure 5. K DPAL output power dependence on pump power demonstrating 52% slope efficiency

optical-to-optical conversion efficiency was about 31%. The maximum output power obtained was about 16 W. These numbers could be even higher if to take into account mismatch between the pump beam and the cavity mode sizes difference. At the same time, the demonstrated efficiencies are significantly higher than those obtained in the same system operating in CW mode [15] that shows possible contribution of limiting effects, such as thermal lensing and ionization. The results of additional research aimed to study the contribution of these limiting effects and possible ways to mitigate them will be published in separate paper.

3. TIME RESOLVED EFFICIENCY DEGRADATION IN POTASSIUM DPAL

For these experiments, we used the same setup (see Figure 2) and the only difference compared to the previous experiment was that the pumping diode laser stack operated in pulsed mode with variable in the range 0.05 – 5 msec pulse duration and repetition rate of 4 Hz. Such a low rep rate minimized the heat contribution from the previous pulse.

In our experiments we recorded both the pump and lasing pulses while varying the pump power in the range from 40 W to 80 W and the K-cell temperature in the range of 165 – 200 C. Figure 6 displays typical shapes of the pump and

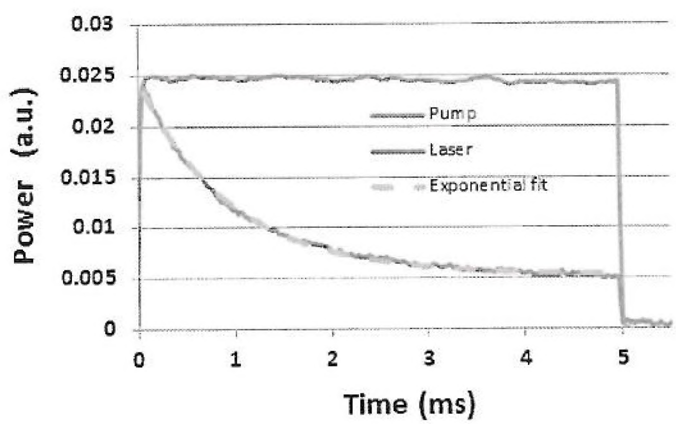

Figure 6. Pump and lasing pulses for a pump power of 73 Watts and a cell temperature of 185 C long with an exponential fit (dashed line) to the decaying lasing pulse

lasing pulses. The pump pulses in all experiments had a nearly rectangular shape, while the lasing power decayed to the level corresponding to CW mode of operation with a characteristic time from 0.5 ms to several ms depending on the cell temperature and pump power. The shape of the decaying pulse could be well fitted by the exponential function:

$$P = P_{cw} + P_0 \exp[-t/\tau], \quad (1)$$

where $P_0 + P_{cw}$ is the peak power, P_{cw} is the asymptotic continuous wave power and τ is the decay time. A typical fit built using this approach is shown in the Figure 6.

The results of measurements of the decay time τ using the fit function (1) for different pump powers and K cell temperatures are presented in Figure 7. The standard error is typically smaller than the symbol used to represent each data point but for those data which had low signal at 165 C the error bars are clearly visible. The trend in the data clearly indicates a decrease of the decay time with increasing cell temperature from 4.5 ms at 165 C to about 0.5 ms at 200 C for all power levels (excluding one point at 165C and 60W pump power, which is close to lasing threshold for this temperature). Also the data reveal that the decay time has a weak dependence on the power. It slightly decreases as the power is increased.

The DPAL power degradation in time observed in these experiments can be attributed to several parasitic processes such as thermal lensing, convection, energy pooling and ionization, which all can decrease density of the active lasing species: neutral alkali atoms and, thus, lower the gain.

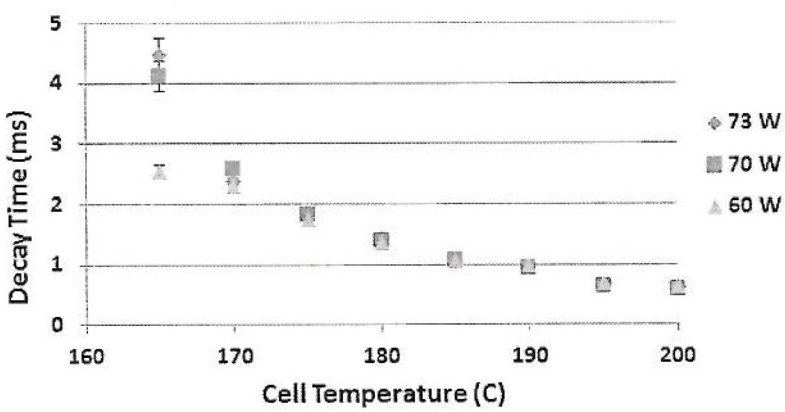

Figure 7. A plot of the decay time with respect to the K cell temperature for different values of pump pulse power.

In addition to the decay data, the spectrum of the side fluorescence from the gain medium was also recorded (see Figure 8). Together with scattered pump and lasing lines, there were several other emission lines identified corresponding

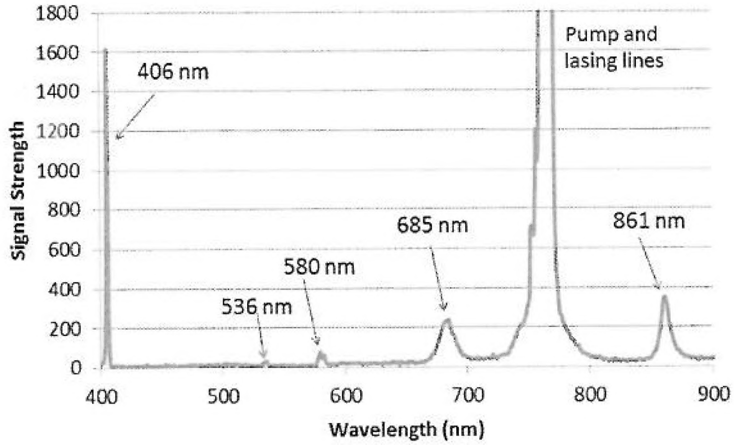

Figure 8. Side fluorescence spectrum from the pulsed, static-cell K DPAL.

to transitions from higher energy levels of excited K. The observed emission lines can be assigned to the following transitions:

> 406± 2 nm corresponds to 5P→4S
> 536± 2 nm corresponds to 6D→4P
> 580± 2 nm corresponds to 5D→4P or 7S→4P
> 685± 2 nm corresponds to 4D→4P or 6S→4P

Evidence of the 4D and 6S states being populated can likely be attributed to direct excitation by the D2 pump and D1 lasing light into the wings of the broadened transitions from the populated 4P state. Observation of the emission lines from higher lying states (6D, 5D, 5P, 7S), which are far off resonance from the D1 and D2 light, strongly suggests that these states are being populated through another process such as energy pooling collisions and/or ionization + recombination within the pumped gain medium [17]. The observed line at 861 ± 2 nm does not coincide with any K atomic transitions and may be attributed to the X→A transition in molecular potassium K_2. For better understanding of these processes, these results should be studied further.

The results of these experiments can be useful when designing a flow system for a high power DPAL because they can help to predict the minimum flow speed required to eliminate the parasitic processes, which degrade DPAL performance, thereby maximizing continuous wave power of the laser system.

As an example, for the case when the cell temperature is 180 C and CW pump power is 10 kW/cm^2 (which corresponds to our experiment demonstrating 52% slope efficiency described above) and assuming a 1 cm long pumped path length in the direction of the gas flow, the minimum flow speed required to alleviate the medium degradation would be about 7 m/s which is relatively modest. Our first experiment with a flowing alkali cell demonstrated significant improvement in the K DPAL operation. In the Figure 9 we present the comparison of the static and flowing cell operation using the same laser cavity and the same pulsed pump with duration 5ms. We plan to continue these experiments with flowing DPAL using longer pump pulses and CW pump.

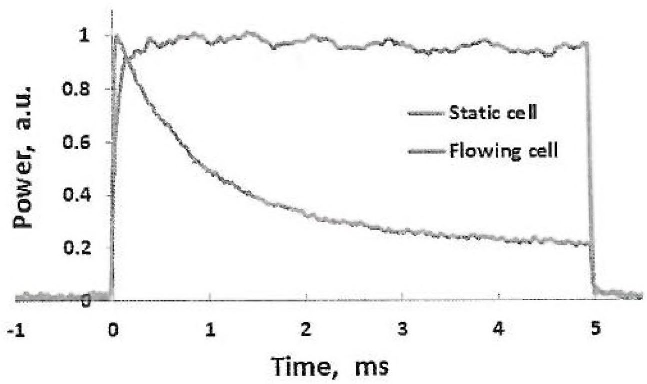

Figure 9. Comparison of the pulsed K DPAL operation using static and flowing alkali cell.

4. CONCLUSION

We have demonstrated a hydrocarbon free potassium DPAL operating in pulsed mode with a slope efficiency of 52% and optical efficiency 30% pumped by a narrowbanded diode laser stack. These numbers are significantly higher than demonstrated in [15] that show possible contribution of limiting effects, such as thermal lensing and ionization, when operating in CW. Additionally, we have examined the performance of a K DPAL operating with a static cell in pulsed mode with pump pulses up to 5 ms. This examination has led to a characterization of the performance decay time as a function of pulse energy and cell temperature. The observed decay times range from 0.5 ms to 4.5 ms and they decrease with increasing of the cell temperature. The observed spectrum of the side fluorescence indicates that multi-photon excitation, energy pooling collisions and ionization may partially explain the observed performance degradation. These results can be used when designing high power DPAL systems and, in particular, they emphasize the need to minimize the operating temperature of a DPAL gain medium.

4. ACKNOWLEDGEMENTS

We acknowledge support of the High Energy Lasers Joint Technology Office who funded this research project.

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From: Ackermann Harro Civ AFRL HEL-JTO <harro.ackermann@JTO.HPC.MIL>
Sent: Thursday, August 21, 2014 2:46 PM
To: ZHDANOV, BORIS V DR CTR USAF USAFA USAFA/DFP
Subject: RE: Manuscript for Sec plus Def Conference
Signed By: harro.ackermann@jto.hpc.mil

Boris,
Sorry for the delay, but here it is....JTO has no objection to the publication of the manuscript "Study of potassium DPAL operation in pulsed and CW mode." Nice paper, just a couple of very minor points for you to consider:

Sect 2, line 3; 'sides' should be 'side'
Sect 2, sentence above Fig 3: 'low signal absorption of ...' sounds funny to me. Perhaps something like 'At low power, absorption of pump radiation.....'

Regards,
Harro

-----Original Message-----
From: ZHDANOV, BORIS V DR CTR USAF USAFA USAFA/DFP [mailto:Boris.Zhdanov.ctr@usafa.edu]
Sent: Monday, August 18, 2014 3:29 PM
To: Ackermann Harro Civ AFRL HEL-JTO
Subject: Manuscript for Sec plus Def Conference

Dear Harro,

Please, find attached the Manuscript titled "Study of potassium DPAL operation in pulsed and CW mode", by Boris V. Zhdanov, Matthew D. Rotondaro, Michael K. Shaffer, and Randall J. Knize, which is summarize our planned presentation at the Security+Defence 2014 Conference held at Amsterdam, Netherlands, on 22-25 September 2014. This paper presents results obtained under the project funded by HEL JTO.
I need your opinion on the publication of this paper.

Thank you,

Boris Zhdanov

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